# ADVANCED TECHNIQUES IN 3D PHOTOLITHOGRAPHY FOR MEMS

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## ABSTRACT

Three dimensional (3D) MEMS fabrication is essential to many power MEMS applications important to today's soldier. We present two advanced techniques to realize 3D structures in photoresist. Both technologies are based on gray-scale photolithography, which is a method to modulate the light intensity incident on photoresist to control the development rate. We compare a commercial technique, HEBS glass, to a technique developed in-house called double-exposure gray-scale. HEBS glass has a better horizontal resolution and is more suited to small structures that require high vertical resolution. Double-exposure gray-scale technology has a comparable vertical resolution to HEBS glass, but is better suited to large MEMS structures over 100μm.

## 1. INTRODUCTION

Micron-scale manufacturing constraints limit traditional micro-electro-mechanical systems (MEMS) fabrication to a planar design regime. Batch three-dimensional (3D) photolithography techniques offer the potential to alleviate design restrictions in the vertical dimension by enabling designs focused on performance rather than manufacturability. However, current concerns in 3D photolithography are vertical resolution and production cost.

In typical photolithography processing, a photosensitive polymer is exposed to ultraviolet (UV) light through a patterned chrome-on-glass optical mask to alter the solubility of the photoresist. The soluble photoresist may then be developed away and the remaining photoresist may be used as a masking layer for further processing steps, such as etching silicon with deep reactive ion etching (DRIE). The patterned chrome on the optical mask is designed to define the planar photoresist features after development. It is possible to achieve 3D patterns in photoresist by locally controlling the UV exposure dose along with the spatial pattern. Spatially varying the exposure dose alters the photoresist development rate and allows for a 3D topography after the development step. This technology is often referred to as gray-scale photolithography due to the varying density of monochrome patterns on the mask. Since traditional opaque features may also be present on the gray-scale mask, the technology is also compatible with traditional photolithography techniques. We review two existing gray-scale techniques and present a third technique that builds on the advantages of both methods.

### 1.1 Applications

An important application of gray-scale photolithography is the realization of 3D silicon structures for power MEMS devices. Personal soldier power of the future may be driven by liquid fueled micro heat engines such as the MIT micro-gas turbine engine currently in development (Epstein, 2004). Utilizing gray-scale technology to fabricate a more complex 3D compressor for the MIT engine (Figure 1), it may be possible to increase engine efficiency by improving the design of the silicon turbomachinery components (Waits, 2005).

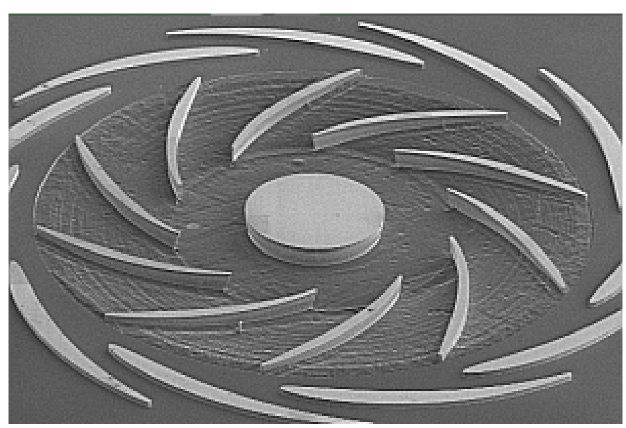

*Figure 1. Variable height silicon micro-compressor fabricated using gray-scale photolithography followed by DRIE.*

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*Form Approved*
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| | | |
|---|---|---|
| 1. REPORT DATE **01 NOV 2006** | 2. REPORT TYPE **N/A** | 3. DATES COVERED **-** |

| | |
|---|---|
| 4. TITLE AND SUBTITLE **Advanced Techniques In 3d Photolithography For Mems** | 5a. CONTRACT NUMBER |
| | 5b. GRANT NUMBER |
| | 5c. PROGRAM ELEMENT NUMBER |
| 6. AUTHOR(S) | 5d. PROJECT NUMBER |
| | 5e. TASK NUMBER |
| | 5f. WORK UNIT NUMBER |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Department of Electrical and Computer Engineering, Institute for Systems Research, University of Maryland College Park, MD, 20742** | 8. PERFORMING ORGANIZATION REPORT NUMBER |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) | 10. SPONSOR/MONITOR'S ACRONYM(S) |
| | 11. SPONSOR/MONITOR'S REPORT NUMBER(S) |

12. DISTRIBUTION/AVAILABILITY STATEMENT
**Approved for public release, distribution unlimited**

13. SUPPLEMENTARY NOTES
**See also ADM002075., The original document contains color images.**

14. ABSTRACT

15. SUBJECT TERMS

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| a. REPORT **unclassified** | b. ABSTRACT **unclassified** | c. THIS PAGE **unclassified** | **UU** | **5** | |

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## 2. METHODS

The UV exposure dose, $d$, incident on a photoresist thin film is defined as:

$$d = i \cdot t \,, \tag{1}$$

where $i$ is the UV light intensity and $t$ is the exposure time. Since the entire mask is exposed at one time, it would be impractical to locally modulate the exposure time. Therefore, gray-scale photolithography uses an optical mask with features that locally modulate the UV exposure dose by changing the intensity incident on the photoresist. The method in which the UV light is modulated is the defining feature of a gray-scale technology.

### 2.1 HEBS Glass

High energy beam sensitive (HEBS) glass technology, patented by Canyon Materials, Inc. (Däschner, 1997), is a high resolution gray-scale technology. In traditional mask making, an electron beam patterns photoresist, which is developed and then used to pattern the chrome layer on the mask. However, using HEBS glass for a masking material, the optical density, which relates to the UV absorbance, can be directly written by a high energy beam. The resulting absorbance at a given location is a function of the beam write time. One advantage of HEBS glass is that the mask will directly modulate the UV intensity, which is the most immediate solution to achieve gray-scale photolithography. Consequently, HEBS glass masks may be used with high resolution contact lithography aligners. Canyon Materials reports that their photomasks are capable of producing more than 500 gray levels with a horizontal resolution of 0.1µm.

#### 2.1.1 Experimental

We created, optimized and examined test structures in photoresist patterned using a HEBS glass mask and contact lithography (Figure 2). We observed a high sensitivity to exposure and development time. We found that AZ9245 photoresist will reproduce about 38% of the designed gray level range on the mask, producing a very high vertical resolution. While HEBS glass masks have a high horizontal and vertical resolution, large, complex designs may become very costly to produce due to the extended write time resulting from the complicated fabrication process.

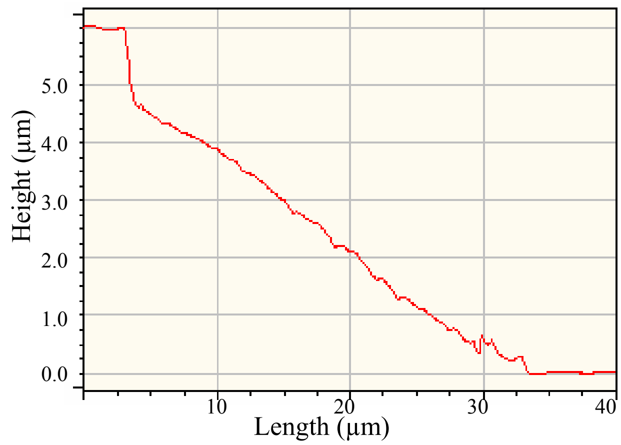



*Figure 2. Profile of a lens structure fabricated using a HEBS glass optical mask.*

### 2.2 Halftone Gray-Scale Photolithography

On projection lithography systems, local exposure dose modulation may be achieved though the use of a halftone (or pixilated) mask, as shown in Figure 3. A halftone mask contains millions of pixels in which the planar dimensions are below the resolution of the projection lithography system. When UV light passes through the sub-resolution pixels, higher order diffractions are filtered by the objective lens and only the $0^{th}$ order intensity, without spatial information, is transferred to the photoresist surface. The dose transferred approximately varies as a function of the relative transparent area (Waits, 2005). If square pixels are arranged in a grid, the distance between the centers of each pixel is called the pitch, $p$, and the length, $l$, is taken as the side of a pixel. Hence, the gray-scale dose, $d_{gs}$, is taken as:

$$d_{gs} = \frac{(p - l)^2}{p^2} \cdot i \cdot t \,. \tag{2}$$

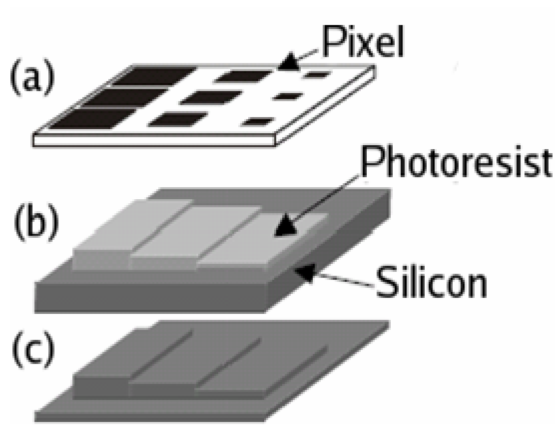



*Figure 3. Pixels on a halftone mask (a) modulate light intensity to create 3D structures in photoresist (b), which can then be etched into silicon (c).*

The maximum pixel length is dictated by the resolution of the projection lithography system, while the minimum pixel length is determined by the fabrication capabilities of the optical mask vendor. Unfortunately, the critical dimension limitations from many mask vendors are not far below the resolution of modern projection

lithography systems, which restricts the available pixel lengths to only a few tens of levels, much lower than the a HEBS glass mask. For example, using a pitch of 2.6μm and a mask written with a 0.1μm address size and a 0.7μm minimum spot size, only thirteen pixels sizes and hence thirteen gray levels are available for device designs (Figure 4). This design limitation may not be adequate for large vertical structures that require higher vertical resolution such as the MIT micro-compressor (Waits, 2005).

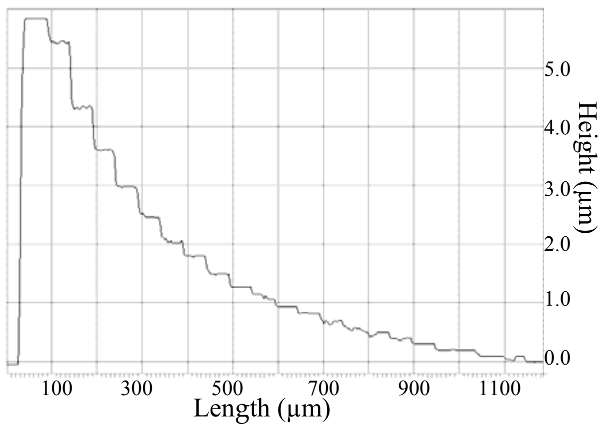



*Figure 4. Profile of photoresist structure created using pixilated gray-scale technology.*

It is possible to further increase the number of gray levels by utilizing rectangular pixels and using a pitch that slightly exceeds the resolution of the projection lithography system. However, using rectangular pixels would increase the design complexity, while increasing the pitch would decrease the horizontal resolution and degrade uniformity since some spatial information from the pixels will be transferred.

## 3. DOUBLE EXPOSURE

As an alternative to HEBS glass, we introduce a double-exposure gray-scale technique, in which two partial halftone gray-scale mask exposures are used prior to a single development. By utilizing two partial exposures, it is possible to achieve dose values not previously obtainable in a single-exposure system.

### 3.1 Experimental

We examined this technique by analyzing a set of six gray-scale pixel sizes which were optimally exposed for a total time of 1.5s in a single exposure. We split this single exposure into two partial exposures with various exposure time ratios, but the same total time to keep development consistent. The experimental mask contains an eight by eight array of 100μm x 100μm squares, where squares on the same row were either transparent, opaque, or comprised of a grid of the same sub-resolution pixels. After completing the first partial exposure, the mask was rotated 180º where squares from a similar grid would overlap to produce every possible combination of pixel size combinations during the second partial exposure (Figure 5).

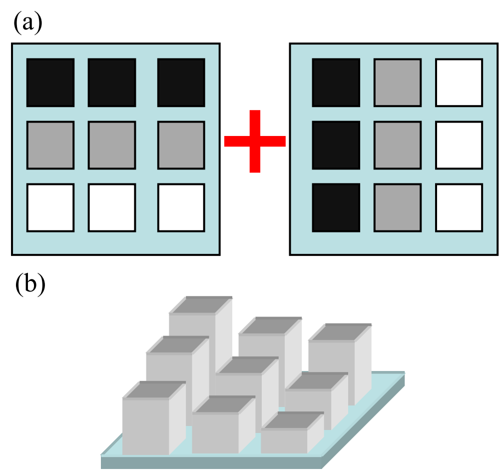



*Figure 5. Two double exposures (a) combine to form every possible gray-scale combination (b).*

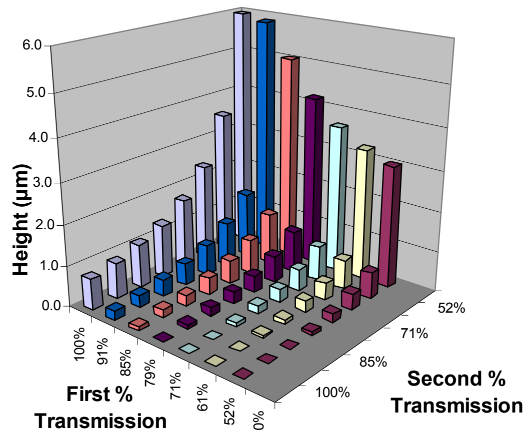
### 3.2 Symmetry

We exposed the grid structure using various exposure time combinations. When the exposure times were the same ($t_1 = t_2$), there were points of symmetry across the diagonal where the order of the same two pixel sizes ($l_1$ and $l_2$) was reversed. We measured the symmetry as the average difference in developed photoresist height for symmetric points. We observed a high degree of symmetry (better than 1.5% of the total resist height) for such exposures (Figure 6). For asymmetric exposures ($t_1 \neq t_2$), we still observed reversibility, which supports that the order of exposure is inconsequential. From this conclusion we adapted equation (2) to give the dose of a double-exposure gray-scale exposure, $d_{degs}$ as:

$$d_{degs} = \frac{(p-l_1)^2}{p^2} \cdot i \cdot t_1 + \frac{(p-l_2)^2}{p^2} \cdot i \cdot t_2 \,. \qquad (3)$$

### 3.3 Vertical resolution

The ideal vertical resolution for double-exposure gray-scale is a function of both the distribution and number of gray-scale levels. Due to symmetry, a symmetric exposure of $n$ levels will result in $n^2/2 + n$ levels. However, asymmetric exposures result in $n^2$ levels in photoresist. It is equally important to control the distribution of levels; otherwise the benefits of a high vertical resolution will come at the cost of a diminished usable photoresist range. Using a simple experimental model from single-exposure experiments we were able to



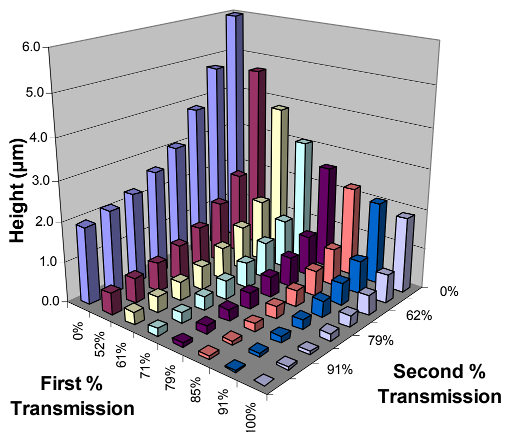




*Figure 6. Photoresist heights from both (a) symmetric and (b) asymmetric double-exposure gray-scale exposures.*

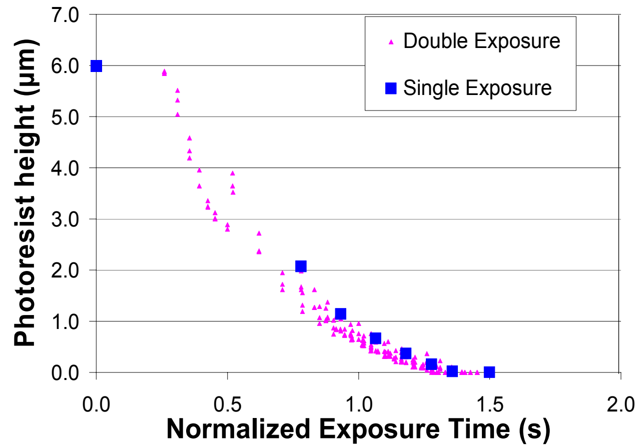



*Figure 7. Experimental results show that double exposure causes an increase in vertical resolution and superior level distribution. Normalized exposure time is the exposure time in seconds multiplied by the relative transmission determined from the pixel size.*

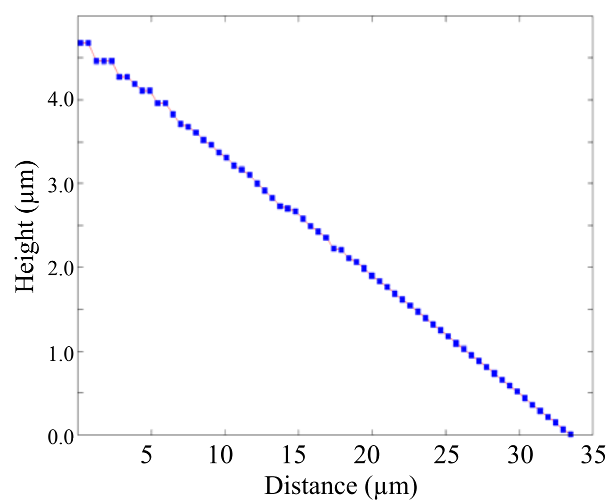



*Figure 8. Linear ramp model designed with the double-exposure gray-scale model*

predict the optimal exposure time ratio with the smallest average step height, where the step height is the difference between one level and the next highest level in photoresist. We calculated that an exposure time of ratio of 2:1 will produce the optimal step distribution. Compared to a single exposure using the same pixel sizes, it is apparent that double exposure has a higher vertical resolution and has achieved a much smoother distribution of heights in photoresist (Figure 7).

### 3.4 Modeling

We have developed an empirical model based on experimental double-exposure gray-scale results for resist height as a function of the double exposure dose. Our model predicts that a 4.7μm tall linear slope will have an average vertical step size of 0.009μm, which can be compared to a vertical step size of 0.19μm using single exposure (Figure 8). Our preliminary design incorporates seventeen pixel sizes and is predicted to produce 289 double-exposure gray-scale levels. However, we expect that designs could incorporate more than 500 levels by utilizing rectangular pixels. Gray-scale test structures will be designed and fabricated to examine the accuracy of the model and evaluate the morphology of double-exposure gray-scale structures.

## 4. DISCUSSION

HEBS glass and double-exposure gray-scale are advanced technologies capable of producing high vertical resolution 3D structures in photoresist. These technologies both have advantages and disadvantages and are well suited for different applications. In terms of vertical resolution, the two technologies are comparable. However, since HEBS glass does not rely on diffraction

and subsequent filtering from projection lithography, it has a higher horizontal resolution of 0.1µm. The double-exposure technique does not improve the horizontal resolution under single-exposure (typically 0.52µm). However, several pixels are required to produce the desired diffraction and filtering effect and hence the achievable horizontal resolution is still lower.

### 4.1 Mask Cost

The cost of the optical mask in both systems is largely due to the tool write time. With HEBS glass technology, the tool has to write longer for areas of the mask that are more absorbent. However, the tool also has the freedom to expose a larger field, causing HEBS glass write times to be sensitive to the level of detail of the structure. Conversely, gray-scale features on pixilated masks must be written at a minimum spot size regardless of feature detail, although opaque features can be written with a larger spot size. While halftone masks require millions of very small pixels, the mask is still written with a single pass of the writing tool and could have a shorter write time depending on the level of feature detail.

Write times for both techniques can be reduced by relaxing the horizontal resolution since it effectively reduces the number of exposure sites. However, for the case of pixilated double-exposure technology, relaxing the mask tolerances can have a much more dramatic effect on the mask cost because. This is because it becomes possible to use a much cheaper, lower-resolution mask writer, such as a laser, that will have a lower starting cost and a smaller charge per minute for overwrite. For example, relaxing the minimum spot size from 0.5µm to 1µm and the addressing from 0.1µm to 0.25µm would allow the use of a lower-resolution mask writer. Such a mask would only have seven gray-scale levels (including transparent and opaque), but double-exposure would allow for 49 levels, which presents a very significant cost-saving solution for structures that do not require very high vertical resolution.

## 5. CONCLUSIONS

We have characterized two 3D photolithography techniques for expanding the MEMS design space to high vertical resolutions. We found that the vertical resolution of both techniques is comparable, though HEBS glass technology has a much higher horizontal resolution. This makes HEBS glass a requirement for structures that require a horizontal resolution on the order of 0.1µm. The optical mask fabrication cost depends largely on the tool choice and the write time, and the HEBS glass write time depends on the complexity of the structure. Therefore, HEBS glass is particularly well suited to large-area structures that can take advantage of a larger spot size, while double-exposure gray-scale technology could prove more economical for highly detailed large-area structures. Also, for applications that are less sensitive to horizontal and vertical resolutions, mask costs could be significantly reduced by using double-exposure technology with a lower-resolution mask writer.

## ACKNOWLEGEMENTS

The Army Research Laboratory (ARL) Collaborative Research Alliance (CTA) Power and Energy program (Cooperative Agreement DAAD19-01-2-0010) supports this research. The authors would like to thank the staff of the ARL for use of their cleanroom facilities and Northrop Grumman for optical mask fabrication. Test structures were fabricated and characterized using the cleanroom facilities at ARL, in Adelphi, MD and at the MEMS Sensors and Actuators Lab at University of Maryland.

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